Advances in plasma heating and confinement in multiple-mirror trap GOL-3

V.V. Postupaev[1,2], A.V. Arzhannikov[1,2], A.V. Burdakov[1,3], I.A. Ivanov[1,2], M.V. Ivantsivsky[1], K.N. Kuklin[1], S.A. Kuznetsov[2], M.A. Makarov[1], K.I. Mekler[1], S.V. Polosatkin[1,2], S.S. Popov[1], A.F. Rovenskikh[1], S.L. Sinitsky[1,2], V.F.Sklyarov[3], N.V. Sorokina[3], A.V. Sudnikov[2], and L.N. Vyacheslavov[1]

[1]Budker Institute of Nuclear Physics, Novosibirsk, Russia
[2]Novosibirsk State University, Novosibirsk, Russia
[3]Novosibirsk State Technical University, Novosibirsk, Russia

INTRODUCTION

During the latest experimental campaign the GOL-3 team continued development of the multiple-mirror confinement concept (see, e.g. [1]) combined with fast collective plasma heating by a high-power relativistic electron beam. Current activity is aimed at search of new experimental scenarios as well as at strengthening of our understanding of underlying physics. We finished experiments with the electron beam of reduced cross-section (see [2]) and returned to older beam geometry. Efficiency of the beam-plasma interaction heavily depends on the beam-to-plasma electron density ratio. Latest experiments were made in a regime when energy and power of the beam gradually grow during the shot. First results from this regime were reported in [3].

In the paper new experimental results are presented. Several diagnostics were put into operation or improved, including two-point two-pulse Thomson scattering, sub-THz radiometry in $2\omega_p$ region, magnetics, fast CCD imaging, exit beam energy spectrum, etc.

DEVICE AND OPERATION REGIME

The device itself is an 11-m-long solenoid with axially-periodical (corrugated) magnetic field [4]. In the basic operation regime the solenoid consists of 52 magnetic corrugation cells with B_{max}/B_{min} = 4.8/3.2 T (the mirror ratio R = 1.5). Deuterium plasma of $10^{20}\div10^{22}$ m^{-3} density is heated up to ~2 keV ion temperature (at ~10^{21} m^{-3} density and τ_E ~ 1 ms) by a high power relativistic electron beam. Typical beam parameters in the standard configuration are ~0.8 MeV, ~20 kA, ~12 µs, ~120 kJ.

New mode of formation of the relativistic electron beam has been tested at GOL-3 for the first time. The waveform of the cathode voltage of the U-2 beam generator was reprogrammed to provide smooth growth from 0.15 to 0.7 MV during approximately 8 µs

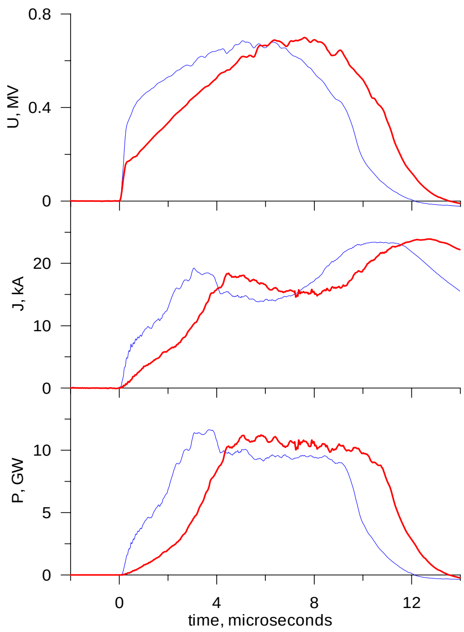

Fig. 1. Main parameters of the electron beam for the standard mode (thin lines) and the mode with smoothly increasing cathode voltage (thick lines). Typical waveforms of the diode voltage (top), the beam current (middle) and the beam power (bottom) are shown.

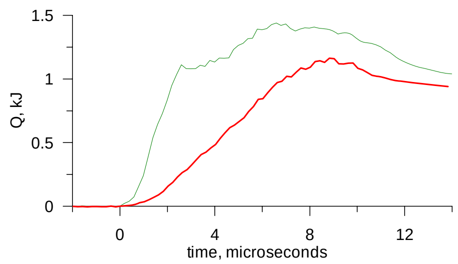

Fig. 2. Dynamics of diamagnetic energy. The standard operating mode is shown by the thin line, the mode with smooth increase in energy of electrons by the thick line.

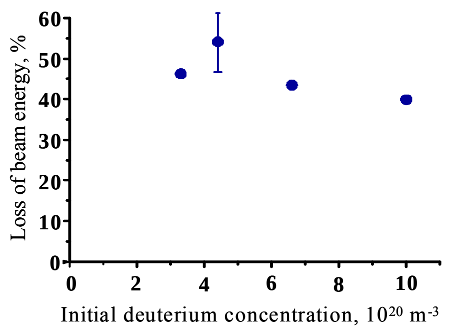

Fig. 3. Maximum beam energy loss vs. initial density. Statistical spread is shown.

(unlike earlier standard mode in which starting voltage was ~0.5 MV), see Fig. 1. Full duration of the beam and its energy content remained practically without changes comparing to the standard mode.

BEAM-PLASMA INTERACTION

A clear feature of previous GOL-3 experiments on plasma heating in the corrugated magnetic field was early transition to the plasma cooling, which occurred much earlier than the beam injection stopped. In the new regime, plasma heating continues until the beam power decreases significantly and results in almost the same final pressure (Fig. 2).

From the point of view of fusion prospects for our concept, optimal beam power should be found that provides collective heating of plasma electrons and maintains suppression of axial heat losses with minimal energy consumption. Despite the lowered beam parameters in the beginning of the pulse the overall beam-plasma interaction efficiency is at the very good level, reaching record 60% of mean deceleration of beam electrons that was measured by an exit spectrum analyzer (Fig. 3). The energy spectrum of the electron flow is strongly broadened from the initial energy of the beam down to lowest measured energy which is 30 keV.

THOMSON SCATTERING DATA

The main target for Thomson scattering system was observation of fast dynamics of axial variation of electron distribution that is strongly non-Maxwellian in GOL-3. The laser beam crosses the plasma twice at coordinates z = 2 and 4 m from the input magnetic mirror. Twin oscillator provides two laser pulses with variable delay (0.1÷100 μs).

Figure 4 shows the plasma density and mean energy of plasma electrons for two time instants (5.5 μs and 8 μs

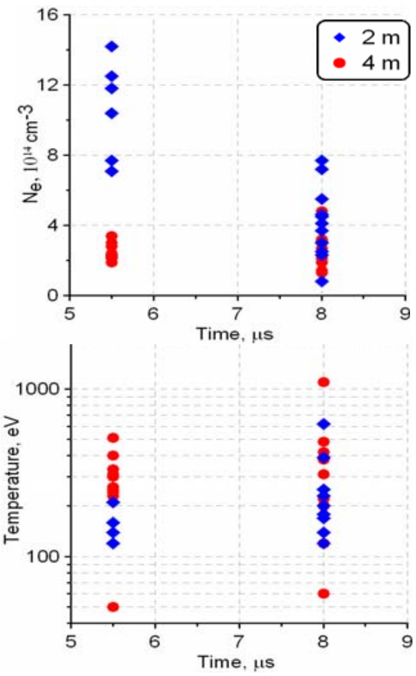

Fig. 4. Single-shot dynamics of density and mean energy of plasma electrons during the plasma heating at z = 2 m and 4 m. A series of plasma discharges is shown.

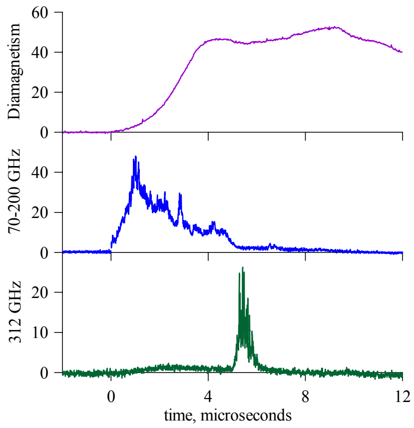

Fig. 5. Raw waveforms, top to bottom: diamagnetism, broadband 70÷200 GHz and 312±35 GHz microwave emission from the plasma.

after the heating start) within a single shot. The data indicate that respectively dense plasma flows along the magnetic field from input plug to the end of facility. So in 2.5 μs the plasma density decreases at z = 2 m but slightly increases at z = 4 m. The mean (transverse) energy of plasma electrons generally increases at both locations however large spread of temperature is noticeable. The more detailed examination of dynamics of plasma electron energy within one shot shows that electron temperature sometimes decreases in the period from 5.5 to 8 μs while the electron beam continues passing through plasma until 11 μs. Such a behavior is basically consistent with the model of collective energy transfer from plasma electrons to ions [5].

SUB-THZ EMISSION FROM THE PLASMA

In the conditions of turbulent plasma heating by a high-power relativistic electron beam there is a possibility of coupling of two Langmuir waves into an electromagnetic wave with double plasma frequency. One of possible generation mechanisms is concerned with occurrence in the plasma localized areas with raised density of Langmuir fluctuations. In this case radiation power dynamics should be formed by a large number of short spikes. This was observed in our previous experiment [6].

Detection system consists of a 250÷450 GHz four-channel quasioptical radiometric system and several newly installed along the plasma 70÷200 GHz broadband detectors. Comparing to our previous measurements the observation point was shifted to the same position as for Thomson scattering system at z = 2 m. Typical raw waveforms are shown in Fig. 5 that clearly demonstrates different dynamics of $2\omega_p$ and lower frequency emission. Dynamics of radial profile of the plasma density can affect the radiation dynamics, so this requires some additional clarification.

PLASMA ROTATION

Plasma rotation was studied with a set of Mirnov coils ant a 250 kfps video. The most significant spatial mode of the magnetic boundary deformation is m = 1 (Fig. 6). Phase

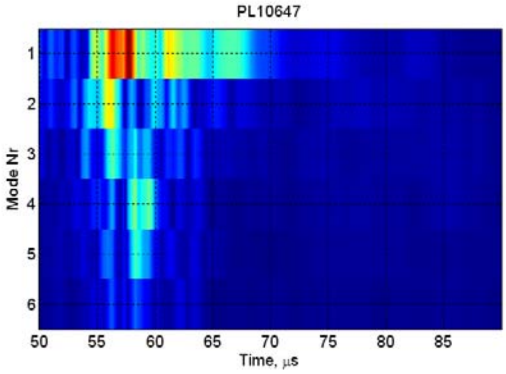

Fig. 6. Mode dynamics of the magnetic boundary deformation.

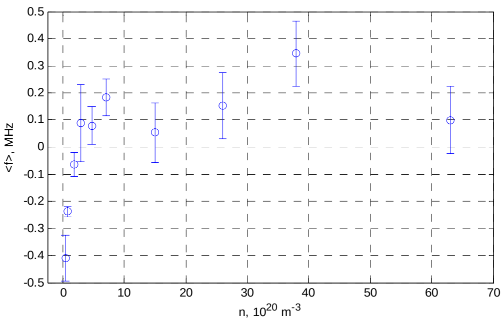

Fig. 7. Frequency of the current boundary

evolution of this mode could be caused by $E\times B$ rotation at $\nu \sim 10^4 \div 10^5$ Hz with the electric field corresponding to the ambipolar potential. Other modes tend to transfer into higher wave number with a timescale ~5 μs.

Usually after the injection of the beam plasma rotation at ~200 kHz is observed. In ~25 μs the frequency reduces gradually to 10 kHz; after that signals become below the useful level. Plasma periphery observed in visible rotates at ~10 kHz during the whole experiment. Therefore the rotation is differential with the shift up to 4π. In low-density experiments below $2{\cdot}10^{20}$ m^{-3} up to 2 revolutions in reversed direction during 15÷25 μs after the end of the beam injection are observed (Fig. 7). Later the direction of rotation restores.

Differential rotation could lead to filamentation of the current structure with the timescale ~3 μs. Signs of the fine structure with current filaments up to 50 A was found in [7].

SUMMARY AND DISCUSSION

Experiments aimed at the development of a physical knowledge base for a mutimirror-trap-based fusion reactor are continued at GOL-3. Special experiments were performed with slow growth of the beam power and energy of the beam electrons in the first half of the beam pulse. Achieved plasma parameters are comparable with the standard regime. New experiments allow us to partially verify feasibility of plasma heating with the electron beam at lowered beam parameters. This is important for the next planned step in GOL-3 program.

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